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Affective visuomotor interaction: a functional model for socially competent robot grasping

Eris Chinellato¹, Gabriele Ferretti² and Lucy Irving¹

¹ School of Science and Technology, Middlesex University, The Burroughs, NW4 4BT, London, UK

² Dipartimento di Lettere e Filosofia, Università di Firenze, Via Bolognese 52, 50139 Firenze, Italy
e.chinellato@mdx.ac.uk

Abstract. In the context of human-robot social interactions, the ability of interpreting the emotional value of objects and actions is critical for robots to achieve truly meaningful interchanges with human partners. We review here the most significant findings related to reward management and value assignment in the primate brain, with particular regard to the prefrontal cortex. Based on such findings, we propose a novel model of vision-based grasping in which the context-dependent emotional value of available options (e.g. damageable or dangerous items) is taken into account when interacting with objects in the real world. The model is both biologically plausible and suitable for being applied to a robotic setup. We provide a testing framework along with implementation guidelines.

Keywords: human-robot interaction, prefrontal cortex, action selection, visual streams, emotional processing, visuomotor processing.

1 Introduction

Due to the ever-increasing diffusion of robots in our lives, Human-Robot Interaction (HRI) is a quickly developing field. It is nowadays considered essential that robots supposed to interact with human partners are not only dexterous, but also offer the appropriate social skills (Pessoa, 2017). Regarding sensorimotor interactions in natural and artificial systems, we currently have a good understanding of the neural mechanisms underlying the visuomotor transformation of object attributes into motor commands, such as identifying graspable portions on the object surface. Such mechanisms have been successfully modeled to produce advanced sensorimotor skills in bio-inspired robotics (Chinellato and del Pobil, 2016). However, in humans and non-human primates (as well as in most mammals), motor behavior in general, and visuomotor representations for grasping in particular, are influenced by the affective perception of the salient properties - encoded from an emotional point of view - of the objects we interact with.

In other words, the representation of object emotionally-relevant properties, or emotional representations, - e.g. perceiving something as dangerous, fragile, etc., can influence, through inhibition (or elicitation), the way in which we represent “affordances”, i.e. the action properties/possibilities (being graspable, climbable, etc.), offered by an object.

In this paper, we review and integrate evidence about affective response to visual stimuli, and the mechanisms subtending reward management, particularly in humans. We aim to extend current models of vision-based grasping in order to include a fundamental additional component, namely, the emotional value that might be associated to performing a certain action or interacting with a particular object. In doing so, we pursue the dual goal of improving robot sensorimotor and social skills, while contributing to the interpretation of fundamental neural mechanisms in the human brain. Endowing a robot with the capability of evaluating environmental stimuli from an emotional point of view, similarly to how a human subject would do, can substantially improve its skills in interacting within the surrounding environment and with human partners in a more effective and competent way. Consider the case of a robot able to ensure human safety by always offering any tool to be grasped by their handles by human partners.

In the next section, we review the current state of the art regarding relevant visuomotor neurosciences and corresponding modeling effort for robotics implementations. Then, we outline our proposal for including the processing of affective information into the typical affordance selection process as performed by bio-inspired robots. We finally outline a possible set of experiments aimed at validating the model presented here and discuss how they could further clarify the nature of the mechanisms at the basis of reward processing during action selection.

2 Background

This section reviews the state of the art in the neuroscience of vision-based grasping, the current state of biomimetic modelling in the field, and the evidence of the role of the prefrontal cortex in informing sensorimotor interactions.

2.1 Visual Neuroscience of Grasping

Modern accounts of visuomotor processing typically build on the two visual streams hypothesis, which suggests the presence, in humans and other mammals, of a separation of the visual pathways, grounded on distinct anatomo-functional structures (Milner and Goodale, 2006): one for visual recognition, the ventral stream, and one for visually guided action, the dorsal stream (Fig. 1). Despite their different roles, the interaction between the streams is crucial in order to shape reliable grasping actions (Chinellato and del Pobil, 2016; Ferretti, 2016, 2018; de Haan et al., 2018).

The dorsal visual stream is divided into (at least) two sub-streams: the medial, or dorso-dorsal stream (D-D) and the lateral, or ventro-dorsal stream (V-D) (Gallese, 2007). Visuomotor transformation of object attributes in motor commands is primarily performed by a defined parietal-premotor network lying in between the parietal cortex and the premotor cortex, that is, a precise portion of the V-D. The main areas involved

in this neural loop are the anterior intraparietal area AIP area and the ventral premotor cortex PMv (roughly corresponding to F5 in monkey studies) (Castiello, 2005; Turella and Lignau, 2014; Borghi and Riggio, 2015; Ferretti, 2016, 2018). AIP extracts visual object information concerning action possibilities for grasping purposes (Theys et al., 2015; Culham et al., 2006; Ferretti, 2016, 2018); the loop with PMv, possibly based on a competitive framework, selects one action to perform, the signal for which is sent to activate the primary motor cortex.

The ventro-dorsal stream areas in the inferior parietal lobe constitute an ideal convergence focus for the integration of semantic ventral information with online sensory data, related to visuomotor processing, from upstream dorsal areas (Chinellato and Del Pobil, 2016; Gallese, 2007; Ferretti 2016).

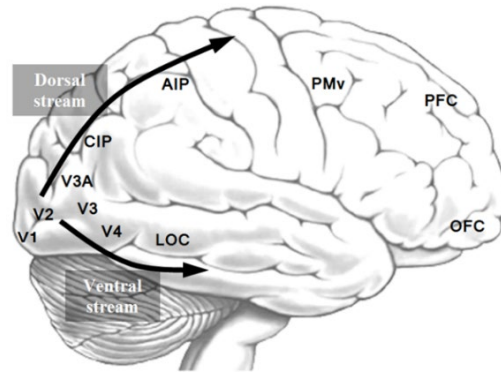


Fig. 1. Dorsal and ventral visual streams, highlighting areas most relevant for processing vision based grasping actions. See Chinellato and del Pobil, 2016 for more details.

Despite its consolidated importance, robotic models of dorsal-ventral interactions are still rare. The conceptual schema in Fig.2 illustrates how dorsal and ventral streams join their efforts to implement appropriate vision-based grasping actions (Chinellato and del Pobil, 2016). No models so far have dealt with the additional role of affective encoding, managed by the prefrontal cortex. In fact, motor behavior in general, and visuomotor representations for grasping in particular, are influenced by the affective representation of the salient properties of the objects we want to interact with, encoded from an emotional point of view. This paper aims to fill such a gap.

2.2 Neural and Psychophysiological Evidence: Visuomotor Interactions and Affective Neuroscience

Evidence from the field of affective neuroscience suggests that the neural correlates of grasping are hugely interconnected with the neural correlates of object affective representations (Anelli et al., 2012). It is worth clarifying the terminology we will be using at this stage. We will be using *affective* and *emotional* as synonyms, referring at the same time to those concepts sometimes described in the neuroscientific literature as *drives* or *motives*. All of these are strongly interconnected with the concepts of value

and reward, as we will see below. The prefrontal cortex (PFC) is considered to be in charge of the organization and orchestration of thoughts and actions in accordance with internal goals and attentional mechanisms (Lebedev et al., 2004). In the specific case of grasping, the PFC is believed to mediate action selection with information on the specific task to perform (Johnson-Frey et al., 2005), integrating information about visual cues, actions, and potential rewards. Such an integration seems to be the main role of the orbitofrontal cortex (OFC), i.e. the orbital sector of PFC.

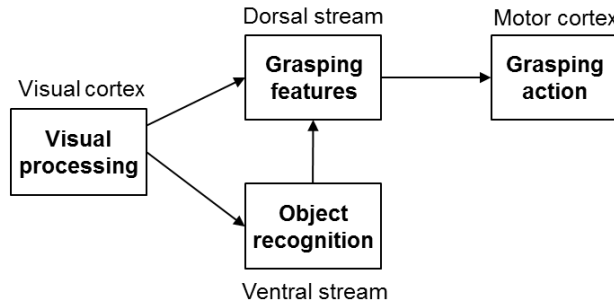


Fig. 2. Vision-based grasping is mediated by the integration of dorsal ventral stream processing (adapted from Chinellato and del Pobil, 2016).

The OFC is subdivided into lateral (lOFC) and medial (mOFC), the latter also known as ventromedial prefrontal cortex (VMPFC) (see approximate locations in Fig. 3). Whilst mOFC appears to be more directly connected to limbic areas, and has a faster response through its magnocellular projections, lOFC has stronger connections to sensory areas, and seems to receive more accurate, but slower, sensory information (Barrett and Bar, 2009). Functionally, lOFC has been observed to process credit assignment, i.e. attributing a perceived reward to the correct stimulus, while mOFC appears to be involved in value-guided decision-making (Noonan et al., 2017). The strong connections of mOFC to other frontal and limbic areas suggest that relative values of options are computed in mOFC taking into account high-level, context-dependent goals. The OFC also has an anterior/posterior subdivision. Its frontal section is more responsive to secondary, deliberative reward tasks (e.g. monetary rewards), while the caudal one is more related to rewards of a primary, instinctive nature (e.g. sexual or food rewards, Sescousse et al., 2010, Klein-Flugge et al., 2013, Keller et al., 2018).

Recent evidence is shedding new light on the nature of the information exchanged by the OFC with many other brain areas (Rolls, 2017). Some studies have highlighted substantial differences regarding the responsiveness of lOFC and mOFC regarding their role in decision-making and reward management. For example, it has been suggested that mOFC processes decision making using reward values provided by lOFC (Rushworth et al., 2012, Noonan et al., 2017). Another possible distinction is the prevalent relation of mOFC with internal motivations (Rolls and Grabenhorst, 2008), compared with external information for lOFC. On the other hand, there seems to be a largely shared role of the various sections of OFC both for predicting reward probability and for potential decision risk (Li et al., 2016). Interspecies differences are pronounced, as

can be expected when dealing with an evolutionary recent cortical area, and data from monkeys or other mammals are only of partial use to derive a model of neural mechanisms in humans (Donahue et al., 2018).

As summarized by Rudeback and Murray (2014), there is substantial consensus on a medial-lateral gradient for relative reward values and a frontal-rostral gradient for reward type:

- **Medial/lateral gradient.** Whereas lOFC assesses options individually according to their implicit affective value, independently from alternative options, mOFC mediates choices by assessing the same options comparatively.
- **Anterior/posterior gradient.** The posterior portion of OFC is specific to primary instinctive rewards, whilst its anterior portion deals with secondary, more deliberative rewards.

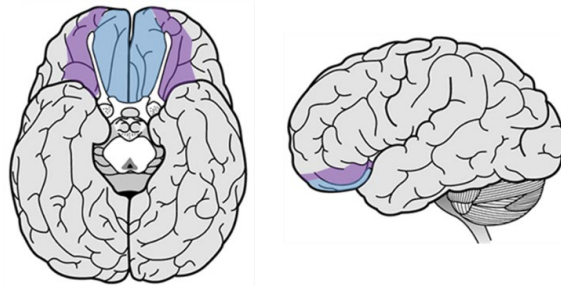


Fig. 3. Lateral OFC (purple); Medial OFC (blue).

2.3 Affective processing in applied models of visuomotor interactions

The analysis of affective and emotional aspects in robotics have been a constant interest for researchers, especially regarding HRI applications (Ziemke and Lowe, 2009). Recent efforts (Jung, 2017; Barros et al., 2018) have been especially devoted to the development of robots more sensitive to human emotions. Specific efforts have been made to model emotions in artificial agents and humanoid robots. These have focused on several important aspects, among which reward management is certainly a very relevant one (Moerland et al., 2018). Other approaches have focused on the importance of episodic memories for complementing sensorimotor interactions through personal experience (Prescott et al., 2019). It is in any case increasingly accepted that intelligent robot design should include an emotional component in order to achieve proper autonomous behaviours in human environments (Pessoa, 2017).

Of particular relevance is the work of Rolls and Grabenhorst (2008), which offers an insight into how neurons in OFC might be able to exhibit certain observed properties. Whilst this is a fundamental reference to take into account, we are more concerned here with higher level functionality and connectivity of OFC, in the context of complex sensorimotor, especially visuomotor interactions.

3 Coupling Visuo-Affective and Visuo-Motor representations for bio-inspired robotics implementation

Pre-activation of premotor and parietal areas upon observation of graspable objects is well established in the neuroscientific literature: the mere observation of objects elicits facilitation effects of motor responses about action preparation (Fadiga et al. 2000). In addition, there is evidence that emotionally relevant properties of objects elicit a correspondent response compatible with their affective valence. For example, dangerous objects that pose a potential risk evoke aversive motor responses, generating an interference-effect (Anelli et al. 2012). In the context of shaping the appropriate response to potential affective rewards during actions selection, the OFC appears to be a critical actor. The conceptual schema in Fig. 4. extends the one shown in Fig.2, by taking into account all the above considerations on affective processing, and how it is expected to intervene during grasping.

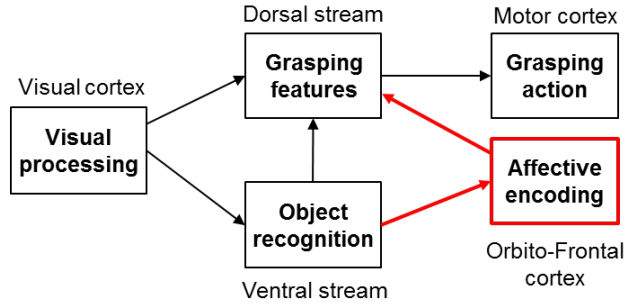


Fig. 4. – The interaction between the streams and the OFC. The affective encoding of the OFC is useful in managing the information encoded by both streams for grasping purposes with respect to affective properties linked to the visual cues offered by the object.

There is currently enough evidence to design a precise framework about how such intervention may occur. We aim to include rather specific functional roles for brain areas and the information flow among them, in order to be able to inform a computational model that can be applied to artificial agents. In Fig.5 we thus propose a functional model implementing the conceptual schema of Fig.4.

We propose here a two-stage account for the role of the OFC in shaping emotionally appropriate motor responses to sensory information about a specific object in a given context (see Fig. 5). We call the two stages of OFC intervention *instinctive* and *deliberative*. The first reaction is mediated by medial and posterior lateral OFC, upon reception of primary stimuli requiring a fast, instinctive response. Such response has been observed for positive rewards (Sescousse et al. 2010), but negative ones should follow the same trend, even more so considering the inconvenience of receiving a potentially painful reward. Known connections linking OFC to premotor cortex through dorsolateral PFC are consistent with such a framework. The second reaction would be through

a *deliberative* pathway, from OFC directly to the striatum in the basal ganglia, a major input to the Inferior Parietal Lobe (IPL) and in particular to the primate grasping area, AIP. The OFC (and particularly the lateral and frontal sections) would thus act as a relay area along a possible ventral-dorsal stream connection, informing the pragmatic processing in the dorsal stream about the affective value of recognized visual stimuli, to be used in action selection and planning. The *instinctive* pathway would follow instead a more direct route to the premotor cortex, exploiting the connections running from mOFC to the premotor cortex, through superior areas of the PFC. The nature of this signal would be the one more traditionally associated with the OFC, i.e. the inhibition of motor plans.

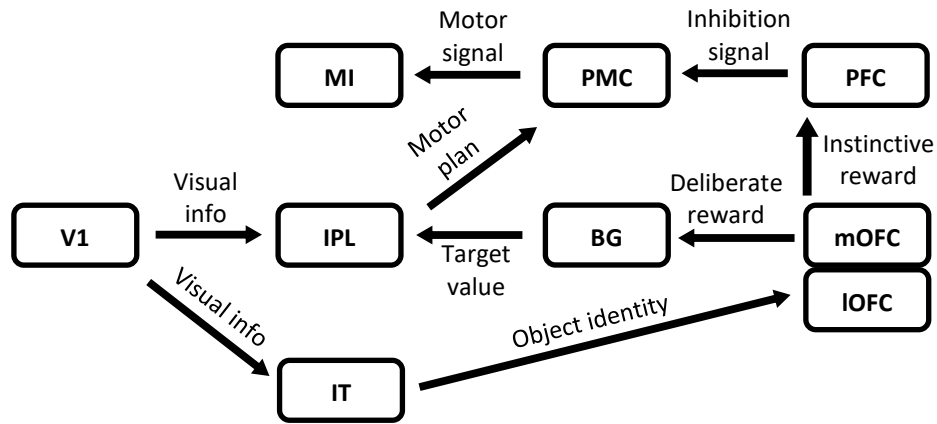


Fig. 5. , Visuomotor affective model, from visual perception (Primary Visual Cortex, V1) to action release (Primary Motor Cortex, MI). Dorsal/ventral interactions is complemented by the visuo-affective representations provided by lateral and medial OFC.

Summarizing, whilst the faster channel running from posterior OFC would be crucial in quickly inhibiting unsuitable motor responses, the slower link to ventral and dorsal areas, through anterior OFC, may be devoted to guiding potential object-related responses that are most salient, or emotionally appropriate, in a given context.

The Basal Ganglia (BG), and particularly the *striatum*, are likely to assume a fundamental role in the above framework. They are involved in mediating between rival perceptions and/or competing motor actions (Clower et al. 2005). They are also strongly connected with the prefrontal cortex. Furthermore, different areas of the basal ganglia project to the dorsal and ventral streams. It seems, thus, that the basal ganglia help establish “go/no-go” responses and reward values concerning motor performance (Munakata 2011), sending the information about such values to the IPL (Nakata et al. 2008; Budisavljevic et al. 2016), either directly or through ventral stream processing.

As explained above, IOFC is likely to assign an absolute reward value to object/action alternatives, whilst mOFC is in charge of comparing those alternatives to perform an informed choice, in accordance to the nature of a given, high-level context. How can this insight fit with the above two stages account? It may be that a single computational process allows to subsume both the *instinctive* and *deliberative* pathways. In such a case,

different activation intensities could evoke information flow in either or both of them. As an alternative, there could be two different processes running concurrently in different sections of the OFC: one for quickly detecting primary reward situation and acting promptly in consequence, and another for processing, more slowly, the convenience of alternative action options associated to secondary rewards. While both alternatives are plausible, the anterior/posterior activation gradients observed for secondary/primary rewards and the nature of the projections to other areas make the second possibility more likely (Sescousse et al. 2010, Klein-Flügge et al. 2013).

Here is a plausible explanation concerning the computational flow at the basis of such a process. Starting from object recognition in the ventral stream, it is plausible to assume that objects/actions related to either primary or secondary rewards are already distinguished in the Inferior Temporal (IT) cortex, considering its strong specialization for stimulus categorization. Projections from IT to the anterior and posterior sections of IOFC would thus proceed in parallel. The IOFC receives information about existing alternatives and estimates the affective value (either positive or negative) for each of them, independently from the other options (Rudebeck and Murray, 2014). Our account assumes that frontal and dorsal IOFC are more strongly connected to frontal and dorsal mOFC, respectively. This seems likely, even though there is still no compelling evidence for it. However, we know that the OFC projects to both superior PFC areas, as well as to the basal ganglia. The proposed hypothesis would thus indicate that stronger connections exist between posterior mOFC and superior PFC, as well as between anterior mOFC and striatum. Therefore, primary reward information would follow the faster pathway leading from mOFC to PM, through dorsolateral PFC, while secondary reward information would reach the dorsal stream through the basal ganglia. Update of reward value according to a given action outcome would be done in IOFC in both cases, but it may well be that learning in anterior and posterior areas may follow slightly different computational solutions.

There is indeed some evidence that the basal ganglia-IPL circuit is based on slower learning processes, akin to standard reinforcement learning. These would be hardly suitable for critical action inhibition, in which even one mistake can be costly, as in the case of dangerous objects. Learning processes subserved by the anterior OFC can indeed progress on a rather typical reinforcement learning framework, in which different objects and action possibilities – as encoded by the ventral stream – are associated to a certain affective value and an appropriate reward signal, somehow proportional to the positive emotional value of each object. Values would be then sent to the IPL through the striatum in the basal ganglia. New experiences can be used to update affective values and rewards. It is also worth highlighting that, especially in humans, such experience does not need to derive from direct experience, but can also depend upon cultural transmission.

The type of signal sent more directly by OFC to the Premotor Cortex (PMC), through lateral PFC, should be of a different nature, more like a strong inhibitory projection, rather than a simple reward value. Equally, learning about strong experiences should be very fast, akin to a single-shot process, rather than a gradual reinforcement learning one. Cultural effects are also likely to assume a significant importance, since we usually prefer to know that something is dangerous before we have any interactions with it.

4 Experimental validation plan

As explained above, visuomotor representations in humans are influenced by emotional aspects, namely, by the representation of emotionally relevant/salient properties: we represent a graspable object as dangerous because we can represent an object as graspable, according to its affordances, and also as dangerous (e.g. because it is sharp, or hot), according to its identity associated with previous experiences or cultural knowledge. The same holds for fragile objects. We might represent an object as fragile, or deformable, and thus graspable under specific conditions: we should ensure a grip that is powerful enough to hold the object but not too powerful to break or crush the object.

The integration of the new frontal functions into neural models for bio-inspired robotic grasping, reported above (see Fig.5) allows us to design new experiments aimed at verifying the influence of the visuo-affective level over standard visuomotor behavior of the robot. We are considering here two different families of objects: dangerous (as in the case of a red-hot object) and damageable (e.g. fragile or deformable). A possible experimental framework for testing our proposal would entail the presence of at least two alternative objects to handle, with choices depending on their aspect and on the action context. Let us imagine a possible set of experiments in which a robot needs to hand the right tool to a human partner.

In a first experiment, the robot would have to choose between two tools (e.g. a wrench and a hammer) according to the task at hand, or directly from human instructions. The robot would observe the two alternative objects, recognize them and judge their suitability for the task. In normal conditions, the match of object identity with an action goal of higher-level would provide the expected reward value for a certain alternative tool. Handing the right (or wrong) tool to a human partner in a certain context would reinforce, or reduce, the connectivity strength of that tool for the task at hand. Making an error would imply a negative reward, and improve the probability of making the right choice in the future.

Let us now consider a second setup, in which one of the two tools (e.g. the one constituting the most appropriate choice in the previous experiment) is recognizably presenting some alarming features. For example, it could be a red-hot metal tool, clearly indicating that handling it would be dangerous (for the robot, the human partner, or both). The importance of the ventral input to action selection in this second setup is clear. Affordance selection, as performed by the dorsal stream, is substantially bypassed by a strong affective bias provided by the ventral input mediated by the frontal cortex. The most typical motor response of the parietal-premotor visuomotor system is inhibited. The most important difference with the previous example is the necessary strength of the ventral influence over action selection. If the wrong action (i.e. grasping the hot object) were ever performed, there would be an extremely strong negative reward, aimed at ensuring that such a choice would never repeat again.

The ventral/prefrontal contribution to action selection could also be observed over alternative actions toward the same object. Let us now consider the third scenario, in which the robot has to handle a fragile object, which, due to its properties, needs to be

grasped with particular care. This could be a precious item, but also a ripe fruit (crushing a ripe fruit in an automated food management line could have strong negative consequences on the whole handling process). Such an object would be graspable only under specific conditions, and the robot should try to avoid a possible damage of the object by using the correct grasping posture and the right amount of force, enough to ensure a solid grip, but not too powerful to damage the object. This case somehow seems to lie in between the two previous experiments: a wrong choice has a strong negative outcome, but not as strong as in the second scenario of a dangerous object. It would be the most interesting case from a computational point of view, as well as for testing the implementation of the proposed approach. The response might be mediated either by the *instinctive* or by the *deliberative* pathway from OFC to motor areas. This would arguably depend on the context, and on the negative or positive affective value associated to a certain outcome. Inhibition coming from frontal mOFC would possibly prevent the object from being grasped at all, while the bias coming from posterior mOFC bias would promote the choice of more careful grasping actions. Further experiments with human subjects would help in verifying the accuracy of such hypotheses.

5 Conclusion

Robotic grasping models aimed at emulating, in robots, the processing of affordance competition we find in humans, are not able to make an emotional evaluation of the environment. This lack of emotional encoding prevents robots from avoiding grasping dangerous objects, or selecting and performing suitable safe grasps on fragile objects.

Visuo-motor-affective evaluation of an object, as proposed in this work, relates to the affective value given to the object in a very specific visuo-motor context and with respect to the goal of the action. According to our proposal, such an evaluation is grounded on anatomo-functional orbitofrontal connections, related to the dorsal and ventral streams, and is able to drive the visuomotor interaction according to emotional considerations about action alternatives. Here we have proposed a two-stage approach capable of explaining common behavior in the presence of emotionally salient objects, while taking into account the state of the art regarding the functionality and connectivity of the orbitofrontal cortex in humans and other primates.

We have offered an overall framework for the model, some guidelines for computational implementation, and an overview of the type of experiments required to validate the model as well as to shed further light on the nature of reward management and action selection as mediated by the OFC.

From a robotics perspective, our model aims to constitute an important step towards including emotional encoding in order to make robots more capable of adapting to the ecological situations they deal with, not only from a visuomotor point of view, but also by relying on visuo-affective computations at the basis of motor responses.

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